# HUBBLE SPACE TELESCOPE FIRST OBSERVATIONS OF THE BRIGHTEST STARS IN THE VIRGO GALAXY M100 = NGC 4321[a]

WENDY L. FREEDMAN[1], BARRY F. MADORE[2], PETER B. STETSON[3]

SHAUN M. G. HUGHES[4], JON A. HOLTZMAN[5], JEREMY R. MOULD[6]

JOHN T. TRAUGER[7], JOHN S. GALLAGHER III[12], GILDA E. BALLESTER[8]

CHRISTOPHER J. BURROWS[9], STEFANO CASERTANO[10], JOHN T. CLARKE[8],

DAVID CRISP[4], LAURA FERRARESE[9], HOLLAND FORD[9],

J. A. GRAHAM[13], RICHARD E. GRIFFITHS[10], J. JEFF HESTER[14]

ROBERT HILL[1], JOHN G. HOESSEL[12], JOHN HUCHRA[15]

ROBERT C. KENNICUTT[16], PAUL A. SCOWEN[14], BILL SPARKS[9],

KARL R. STAPELFELDT[7], ALAN M. WATSON[12], JIM WESTPHAL[17]

Received............................................

Address for Proofs:

Wendy L. Freedman
The Observatories of the Carnegie Institution of Washington
813 Santa Barbara St.
Pasadena, California 91101

Running Headline: *RESOLVED STARS IN VIRGO*

[a] Based on observations with the NASA /ESA *Hubble Space Telescope*, obtained at the Space Telescope Science institute, which is operated by AURA, Inc. under NASA Contract No. NAS 5-?6555.

[1] The observatories, Carnegie Institution of Washington, Pasadena, CA 91101

[2] NASA/IPAC Extragalactic Database, Infrared Processing and Analysis Center, (California Institute of Technology, Pasadena, CA 91125

[3] Dominion Astrophysical Observatory, 5071 W. Saanich Rd., Victoria BC V8X 4M6

[4] Royal Greenwich observatory, Madingley Road, Cambridge, UK, CB3 0EZ

[5] Lowell Observatory, Mars Hill Road, Flagstaff, AZ 86001

[6] MSSSO, Weston P. O., ACT 2611, Australia

[7] Jet Propulsion Laboratory, 4800 Oak Grove Dr., Mail Stop 169-237, Pasadena, CA 91109

[8] University of Michigan, Dept. of Astronomy, Dennison Bldg., Ann Arbor, MI 48109-1090

[9] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

[10] Dept of Physics & Astronomy, Bloomberg 501, Johns Hopkins Univ., 3400 N. Charles St., Baltimore, MD 21218

[11] Lick Observatory, University of California, Santa Cruz, CA 95064

[12] University of Wisconsin, Madison, Dept. of Astronomy, 475 N. Charter St., Madison, WI 53706

[13] Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Rd. N.W., Washington D.C. 20015

[14] Arizona State Univ., Dept. of Physics & Astronomy, Tyler Mall, Tempe, AZ 85287

[15] Harvard College, Center for Astrophysics, 60 Garden Street Cambridge, MA 02138

[16] Steward Observatory, University of Arizona, Tucson, AZ 85721

[17] California Institute of Technology, Pasadena, CA 91125

## ABSTRACT

As part of both the *Early Release Observations* from the *Hubble Space Telescope* and the *Key Project on the Extragalactic Distance Scale*, we have obtained multi-wavelength BVR WFPC2 images for the face-on Virgo cluster spiral galaxy M100 = NGC 4321. We report here preliminary results from those observations, in the form of a color-magnitude diagram for ~11,500 stars down to V ~27 mag and a luminosity function for the brightest blue stars which is found to have a slope of 0.7, in excellent agreement with previous results obtained for significantly nearer galaxies. With the increased resolution now available using WFPC2, the number of galaxies in which we can directly measure Population 1 stars and thereby quantify the recent evolution, as well as test stellar evolution theory, has dramatically increased by at least a factor of 100. Finally, we find that stars are present in M100 at the colors and luminosities expected for the brightest Cepheid variables in galaxies.

*Subject headings:* galaxies: distances - galaxies: individual (M100 = NGC 4321) stars: Cepheids - stars: OB stars

## 1. INTRODUCTION

M100 (NGC 4321) is a luminous spiral galaxy in the Virgo cluster that is seen nearly face-on, with an apparent axial ratio of 0.87; Tully 1988). Having very well-defined symmetric spiral arms, it is classified by Sandage and Tammann (1981) as Sc(s) I and by de Vaucouleurs *et al.* (1976) as SAB(s)bc. From the ground this galaxy is not well-resolved, and little was previously known of its stellar populations.

As part of the *Early Release Observation* program associated with the initial commissioning phases of WFPC2, M100 was imaged in three filters and at two epochs. The purpose of these observations was to provide both a test of the corrective optics and a feasibility study of Virgo cluster observations for the *Extragalactic Distance Scale Key Project.* The Key Project was begun in December 1992 using WF/PC (WFPC1) to observe the nearby galaxy M81; a distance to that galaxy based on the HST discovery of 30 new Cepheids has recently been published by Freedman *et al.* 1994. The calibration procedure and a discussion of the stellar populations was given in Hughes *et al.* 1994. The primary aim of the Key Project is to measure Cepheid distances to about two dozen nearby galaxies useful for calibrating a number of secondary distance methods. In addition, the Key Project target list includes 4 galaxies in the Virgo cluster, one of which is M100.

A well-determined distance to the Virgo cluster is important for many reasons. Due both to its proximity and the fact that it contains a wide range of galaxy types, a large number of secondary-distance techniques have been applied to this cluster. The distance to the Virgo cluster has been a focal point for discussion because published values have spanned a wide range: the 'long' and the 'short' estimates of the extragalactic distance scale. It is now generally agreed that the distances to galaxies within the general vicinity of the Local Group (out to $\sim$1 Mpc) have been obtained to an accuracy and precision of $\pm$10% (Fukugita *et al.* 1993). But current estimates for the distance to Virgo (15 - 21 Mpc: *e.g.* Jacoby *et al.* 1992; up to 27 Mpc: Sandage 1993) differ by the uncertainty commonly associated with the far-field value of tile Hubble constant itself.

The core of the Virgo cluster is devoid of spiral galaxies; hence the *most appropriate target* in Virgo is M100, which is 4° NW of M87. Finding Cepheids in M1 00 will not lead to a decisive measurement of the Virgo distance since the Virgo cluster is thought to extend from 10 to 18 Mpc (Tonry *et al.* 1990), and further in Virgo South. Nevertheless, a distance to a Virgo galaxy is a critical test of the competing distant.c scales. Furthermore, an increasing amount of information about the structure of Virgo is becoming available. For example, Fouque *et al.* (1990) have found that the 20 nearest spirals to M100 (within '20), are ().37 ± 0.17 mag closer than the Virgo cluster mean. Virgo is located approximately 16 Mpc away according; to the short distance scale; hence 20-day Cepheids in Virgo would be predicted to have < V > = 26 mag. If Virgo is located at the long distance of approximately 27 Mpc (Sandage 1993), the 'X)-clay Cepheids arc predicted to be more than a magnitude fainter. For these reasons, we have placed high priority on observing M 100.

in the long term, direct Cepheid distances to a significant sample of Virgo galaxies will settle tile controversy over the the short and long distance scales for the cluster itself: a vital step, since it is currently the uncertainty in the distance rather than the velocity, that plays the critical role in the present controversy over the value of the Hubble constant. Moreover both the Virgo and Fornax clusters have an important role to play in calibrating secondary distance indicators which tie the local distance measurements to the global expansion.

Before the repair of the optics for HST, resolved studies of the most luminous stars in spiral galaxies were confined primarily to those within the Local Group or within nearby groups such as those associated with M81 and M1 01. (For a review of studies of luminous supergiants in external galaxies see, for example, Humphreys 1987; Cepheid studies have been reviewed by Madore & Freedman 1991; and J acoby *et* al. 1 992). Recently, some ground-based measurements of the brightest objects in Virgo galaxies have been carried out under excellent sewing conditions (~

0.4-0.6 arcsec) by Shanks *et al.* (1991) and Pierce, McClure, & Racine (1992). With the wide-field camera / planetary camera the effective resolution at Virgo is 5× / 10× higher than can presently achieved from the ground, and is comparable to observing M81 from the ground at ~0.5 / ~0.25 arcsec resolution, or observing typical Local Group galaxies with ~2 / ~1 arcsec resolution

In this *Letter* we present color-magnitude diagrams and luminosity functions for the brightest objects in M100. In addition to the brightest stars, we identify several young clusters and inner regions of associations in the spiral arms. Finally, the feasibility of discovering Cepheids in this galaxy using HST is discussed. The M100 nucleus is the subject of another paper by Gallagher *et al.* (1994); photometry of the clusters will be presented by Madore *et al.* (1994).

## 2. THE OBSERVATIONS, REDUCTIONS AND CALIBRATION

Data were obtained with WFPC2 at two separate epochs separated by 7 days: 1993 December 31 and 1994 January 7. On both dates the WFPC2 was oriented at an angle (V3) of 109 degrees in such a way that the high-surface-brightness nucleus was imaged on the Planetary Camera (PC) and the three 1.3 x 1.3 arcmin Wide Field Camera (WFC) chips were located on spiral arms and other regions eastward of the nucleus. The F555W (V) images for the four chips shown in Figure Exposure times were as follows: F439W (4 × 900 sec), F555W (3 × 900 sec and 769 sec), F702W (5 × 600 sec and 519 sec). The latter exposures at F555W and F702W were cut short because of a loss of lock on the guide stars. Short integrations (5-60 sec) were also taken so that unsaturated images of the nucleus could be obtained. However, for the purposes of the stellar photometry here, only the integration frames were included in the

The M100 frames were processed using calibration data from the WFPC2 ground thermal-vacuum (TV) test. The initial processing of the individual raw frames consisted of a very small A/D correction, subtraction of a bias level and superbias frame, subtraction of a superdark frame, and a tiny shutter shading correction. Subsequently, the frames in each filter were combined to reject cosmic rays. Pixels in each frame that deviated by more than 5 sigma from the mean in the remaining frames were rejected; neighbors of these pixels were rejected with a 3 sigma threshold. Finally, the averaged frames were flattened using flats from the TV trots to remove high spatial frequency response variations, and using a model of the HST plus WFPC illumination pattern to remove low spatial frequency variations. From subsequent on-orbit flats, the flat-fielding used for the M100 frames is estimated to be good to a few percent 1111s, with peak errors of $\sim 10\%$ in the corners of each chip.

An initial pass at the photometry of the averaged, cosmic-ray-cleaned frames was made using the aperture photometry routine available in the software package DAOPHOT II (e.g. Stetson ]992 and references therein). Later, profile-fitting photometry was obtained (as described below) on the original, unaveraged frames. A comparison of the aperture photometry between the averaged and unaveraged frames yielded differences amounting to less than 1 %.

Profile-fitting photometry of the original frames was performed using DAOPHOT 11 and ALLFRAME (Stetson 1994a). The point-spread functions (PSFs) were obtained with the stand-alone routine MULTIPSF (Stetson 1994b). Because of a shortage of bright, well-exposed yet unsaturated stars in the Virgo images, PSFs were determined from images of the calibration field in $\omega$ Centauri. A separate PSF was generated for each chip/filter combination; those for the three Wide-1'icld Camera chips were allowed to vary quadratically as a function of position in the image, while that for the Planetary Camera was treated as being constant. During the ALLFRAME reductions themselves, inner and outer radii for the sky annuli were set at 0.7 and 6.0 pixels for the WFC chips, and 0.7 and 8.0 pixels for the PC chip. The inner radius was set at this low value in order to 1) determine the sky as c.1osc to the stars as possible, 2) determine the sky brightness from pixels where the star is as bright as possible with respect to the sky, and 3) determine the sky from those pixels from which it has not been necessary to subtract a large amount of star flux. Note that sky determinations were periodically refined after *all* detected objects had been provisionally subtracted from the images; thus, the photometric magnitudes should be relatively unaffected by the patchiness of the diffuse flux in M100 that occurs on spatial scales larger than a few pixels.

The frame-to-frame repeatability of stars measured in WFPC2 images - both those of M100 and of $\omega$ Centauri, as well as numerous simulated images was found to be $\sim$ 0.03 mag per exposure for stars from just below the magnitude level of incipient saturation to a magnitude level about four magnitudes fainter. Below that, the errors increased in reasonable agreement with what would be expected from photon statistics. External errors will be larger, and cannot be estimated from our repeat observations since the field always fell identically on the chips. A further source of uncertainty comes from the recently discovered problem with charge-transfer efficiency (see below). The $\omega$ Centauri images suggest that position-dependent systematic errors may be as large as of order 5-7% (NO. 1 mag), root-mean-square, but this result is based only on a few dozen stars in only six separate WFPC2 observations.

The transformation from the instrumental (F439W, F555W, F702W) to the standard Johnson-Kron-Cousins BVR system was accomplished in two steps. First, using data for stars in the field of the globular cluster $\omega$ Cen, a transformation was made from the WPFC2 instrumental magnitude system to the WFPC1 system, as defined by Harris *et al.* (1993). Details of this calibration procedure undertaken by the WFPC2 team are given by Holtzman *et al.* (1994). Finally, the transformations given by Harris *et al.* (1991) were used to transform to the standard BVR system.

Subsequent to these observations, it was discovered that there are charge-transfer problems with the WFPC2 chips at the operating temperature used for these observations (- 77C). This charge-transfer problem leads to variations in effective sensitivity depending on the row number in which an object falls. The effect gives a gradient of approximately 10% in the photometry for the calibration data used here, but is possibly reduced in the M100 data which has a significant background (from the light of unresolved stars). Because of this effect, as well as scatter in the flight and ground observations of the calibration fields, the photometric zeropoints could be off by several (.5-10) percent, and there is possibly a gradient in the photometry across the M100 frames leading to an effective additional rms error of ~ 3 - 5 percent when objects over the entire field are considered. For these reasons, the photometry presented in this paper should be considered as preliminary only.

## 3. COLOR-MAGNITUDE DIAGRAMS AND LUMINOSITY FUNCTION

ALLFRAME photometry was obtained for a total of 30,551 stars and star-like objects in the three WFC fields, and a further 1580 objects in the PC field. Not all objects were detectable in all filters, however, and various goodness-of fit criteria were used to further limit the sample of objects discussed below. Stringent CHI restrictions were placed on the data to minimize the contamination by clearly resolved, non-stellar objects.[1] The resulting V versus (II--V) color-magnitude diagram for the WFC chip 3 is shown in Figure 2. Plotted are ~11,500 stars with ALLFRAME CHI < 1.4. About 12% of the total objects measured were eliminated on the basis of this stringent CHI limit.

The brightest blue supergiants in the color-magnitude diagram have V ~ 22.5, B - V ~ 0.2 mag. Present also are red supergiants with V ~ 22.7, B - V ~ 1.5 msg. The solid lines represent

[1] For readers who are not DAOPHOT aficionados, CHI is the ratio of the observed rms pixel-to-pixel residual of the actual image data from the best-fitting scaled model PSF to that rms residual predicted from readout noise, photon statistics, flat-fielding uncertainty, and anticipated interpolation imprecision (i. e., the ratio of observed to expected rms residual). If the noise model is correct, the average value of CHI should be close to unity; any object with CHI >> 1 is probably nonstellar.

the mean Cepheid instability strip (described Mow). Fainter than V = 22 mag contamination by foreground Galactic field stars is negligible in the 1.8 square arcmin area of a single WFC2 chip (Bahcall & Soneira 1981; Ratnatunga & Bahcall 1985); therefore, essentially all of the measured sources contributing to Figure 2 belong to 14100.

Stars with CHI > 1.4 were flagged as potential star cluster candidates. A plot of CHI versus magnitude revealed that over the range of the brightest 2 magnitudes, almost all objects had large! CHI values (> 1 .4). The brightest objects in the initial candidate list were then inspected by eye to eliminate spurious objects or irregular-shaped asterisms that were more likely duc to chance image crowding. Most of these clusters arc very blue (B - V ~ ().2 mag) and are thus young. Many of these objects have FWHM intensity-diameters of < 0.5 arcscc and thus would appear to be stellar in most images taken with existing grouncl-based telescopes. Interestingly, there appears to be a ri])g-like concentration of compact star clusters around the periphery of the nuclear disk. These clusters will discussed in more detail in a future paper (Madore *et al.* 1994).

A luminosity funct ion for the blue supergiants is shown in Figure 3. A line of slope 0.7 (the mean slope determined by Freedman (1985) for a sample of 10 nearby spiral and irregular galaxies) is superposed on the M100 data; the agreement is excellent. This result extends and confirms earlier work indicating that, to within the uncertainties, the slope of the upper end of the luminosity function appears to be universal for galaxies with a wide range of morphological types and metallicities.

In Figure 2 the Cepheid instability strip (Madore & Freedman 1991) is plotted after having been shifted by 31.3 magnitudes in apparent distant.c modulus (an illustrative mean value of the Virgo modulus, based on measurements of 7 independent secondary distance indicators tabulated by Jacoby *et al.* 1992). in 'J'able 1, the expected (unreddened) V magnitudes for Cepheids of 20, 40, and 60 clays arc given for apparent distance moduli of 30.9 and 31.5 mag, based on the above-cited period-luminosity calibration. These distance moduli correspond to 15 Mpc and 20 Mpc respectively. A 40-day Cepheid will have $< V >\sim 25.1$ mag if Virgo is at the closer distance and $< V >\sim 25.7$ mag if Virgo is at the farther distance. If the Virgo cluster is as distant as 27 Mpc or $\mu \sim = 32.2$ mag), the 60-day Cepheids would still have $< V >\sim 25.9$ mag, a magnitude limit well within the reach of WFPC2 (sew Figure 2).

Table 1 - Unreddened Cepheid V Magnitudes as a Function of Distance

| PERIOD (days) | 15 Mpc ($\mu$ = 30.9) V magnitude | 20 Mpc ($\mu$ = 31.5) V magnitude |
|---|---|---|
| 20 | 25.9 | 26.5 |
| 40 | 25.1 | 25.7 |
| 60 | 24.6 | 25.2 |

The exposure times for the *Early Release Observations* at each individual epoch were short (in total less than 1800 sec at V and 1200 scc at R). Hence an improvement in sig]lal-tc)-noise ratio can be achieved with longer exposures. Moreover, the effects of crowding can be decreased by working at a lower surface brightness level at greater radial distance from the nucleus. Finally, the PC can be used to full advantage (with its increased sampling of the PSF) by positioning it away from the nucleus in an active star-forming region where Cepheids are expected to be located. Based on these preliminary data we conclude that the discovery of Cepheid variables in M100 is feasible using WFPC2, and our scheduled Key Project observations (optimized as described above) arc now underway.

## 4. SUMMARY

Above all, the results of this paper demonstrate the impressive capability of HST for studying the resolved stellar populations in galaxies well beyond the Local Group. BVR color-magnitude diagrams and a luminosity function for the brightest blue supergiants have been measured in a galaxy at a distance representative of the Virgo cluster. These results demonstrate that we now have the potential to study the rich variety of galaxies present in the Virgo cluster with comparable resolution to that of several galaxies in our own Local Group; moreover for galaxies closer than those in the Virgo cluster, the resolution will be even greater. In M100, we find the slope of the luminosity function to be in agreement with that previously measured for supergiants in nearby galaxies. Several prominent blue clusters and dense regions in associations have been idenified. Star-like objects with magnitudes and colors expected for Cepheid variables at the distance of Virgo have been detected in M1OO, thus demonstrating the feasibility of determining light curves for actual Cepheid variables in the most distant of our target galaxies. Follow-up observations of an adjacent and partially overlapping field in M100 have now begun with the aim of discovering and determining periods for Cepheids in this galaxy, an important step in the 11 ST Key Project on the Extragalactic Distance Scale.

## Acknowledgments

Support for this work was provided by NASA through grant number 2227-87A from the Spat.c Telescope Science Institute which is operated by the Association of Universities for Research in Astronomy Inc. under NASA Contract NAS5-26555. BFM was supported in part by the Jet Propulsion Laboratory, California Institute of Technology, under the sponsorship of the Astrophysics Division of NASA's Office of Space Science and Applications. WLF's work on the extragalactic distance scale is supported in part by NSF Grant No. AST 91-16496. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, Caltech, under contract with NASA.

## Figure Captions

Fig. 1 - A montage of the 4 WFPC2 F555W images for the observed M100 field.

Fig. 2 V versus (B - V) color-magnitude diagram for ~11,500 stars measured by ALLFRAME on WFC2 chip 3. The solid lines indicate the position of the unreddened mean Cepheid instability strip for a distance modulus of 30.3 mag (18 Mpc). The corresponding magnitude levels appropriate for this distance modulus for periods of 10, 20, 40, and 60 days are labelled.

Fig. 3- V-band luminosity function for the brightest blue stars in Ml 00.

## References

Bahcall J. N., & Soneira R. M. 1981, *Ap. J. Suppl.*, 47, 357

de Vaucouleurs, G., de Vaucouleurs, A., & Corwin, H. G., Jr. 1976, Second Reference Catalogue of Bright Galaxies, (University of Texas: Austin)

Fouque, 1'., Bottinelli, L., Goughenheim, L., & Paturel, G. IWO, *Ap. J.*, 349, ]

Freedman, W. 1,.1985, *Ap. J.*, 299, 74

Freedman, w. 1,., *et al.*,, 1994, ApJ., June 10 issue, in press

Fukujita, M., Hogan, C., & Peebles, 1'. J. E., 1993, Nature, 366, 309

Gallagher, J. S., *et al.* 1994, *Ap. J. Lett.*, in preparation

Harris 11. C., Baum W. A., Hunter D. A., Kreidl 'J'. J. 1991, *A. J.*, 101, 677

Harris H. C., Hunter 1). A., Baum W. A., Jones, J. 11. 1993, *A. J.*, 105, 1196

Holtzman, J., *et al.*. 1994, WFPC2 Preliminary Status Report, 16 March 1994

Hughes, S. M. G., *et al.*,, 1994, ApJ., June 10 issue, in press

Humphreys, R. M. 1997, *Publ. A. S. P.*, 99, 5

Jacoby, G. 11. *et al.* 1992, *Publ. A. S. P.*, 104, 599

Madore, 11. 1'., & Freedman, W. 1,.1991, *Publ. A. S. P.*, 103, 933

Madore, B. 1"., *et* al. 1994, *A. J.*, in preparation

Pierce, M. J., McClure, R. D. & Racine, R. 1992, *Ap. J.*, 393, 523

Ratnatunga K. U. & Bahcall J. N. 1985, *Ap. J. Suppl.*, 59, 63

Sandage, A. R. 1993, *Ap. J.*, 402, 3

Sand age, A. R. & Tamman n, G. A. 1981, *A Revised Shapley-Ames Catalog of Brigh t Galaxies*, (Washington, D.C.: Carnegie institution)

Shanks, 'J'., Tanvir, N. R., Major, J. V., Doel, A. 1'., Dunlop, C. N., & Myers, R. M. 1992, *M. N. R. A. S.*, 256, 29])

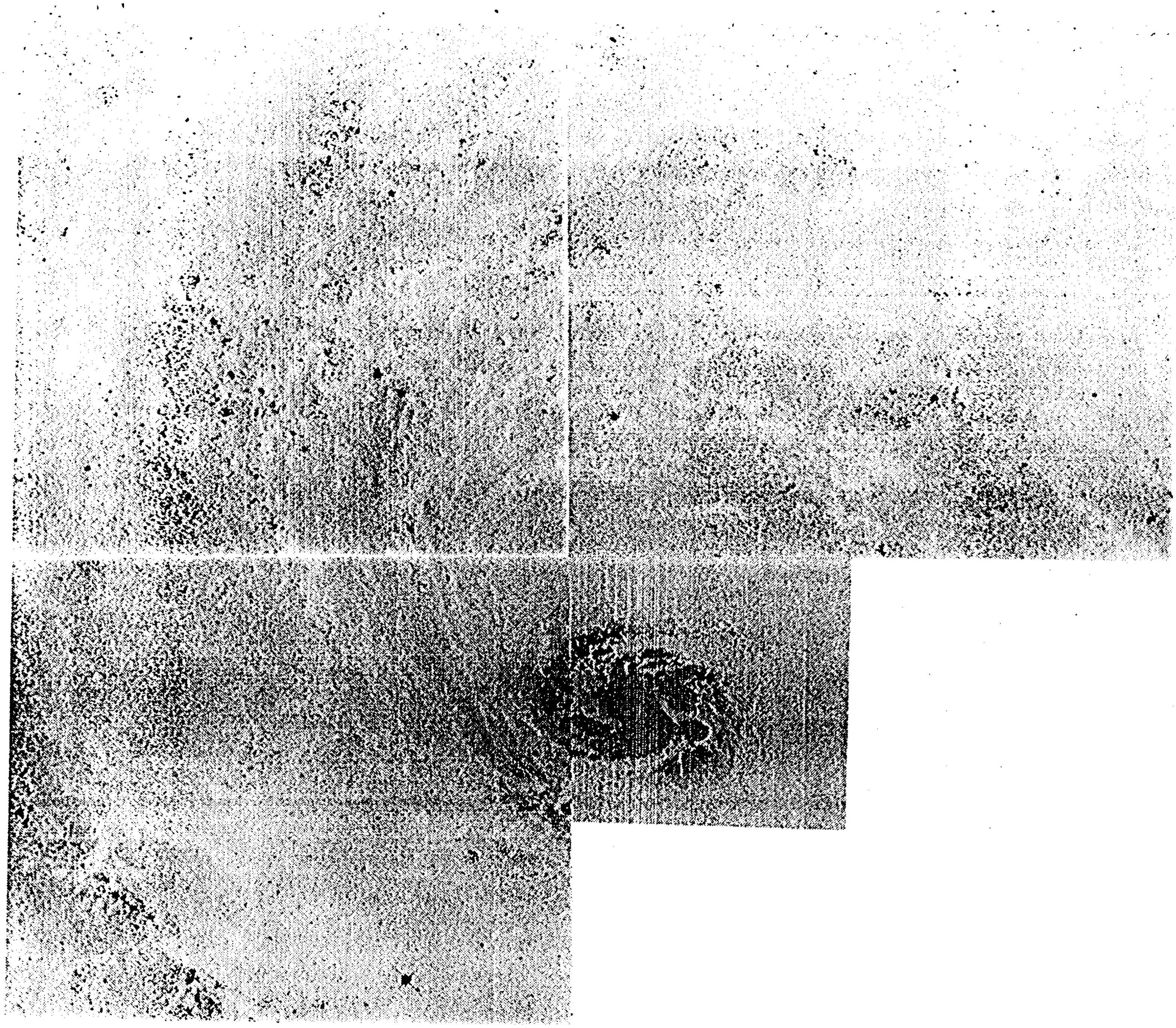
Stetson, P. B. ] 992, in A *stronomical Data Analysis Software & Systems I*, eds. D. M. Worrall, C. Biemesderfer, and J. Barnes, PASP Conf. Ser., 25, 297

Stetson, 1'. 11.1 994a, *Publ.* A. S. *P.*, 106, 250

Stetson, 1'. B. 1994b, to app ear in proceedings of Space Telescope Workshop on Calibration of HST Data

Tonry, J. 1,., Ajhar, E. A., & Luppino, G. A. 1990, *A. J.*, 100, 1416

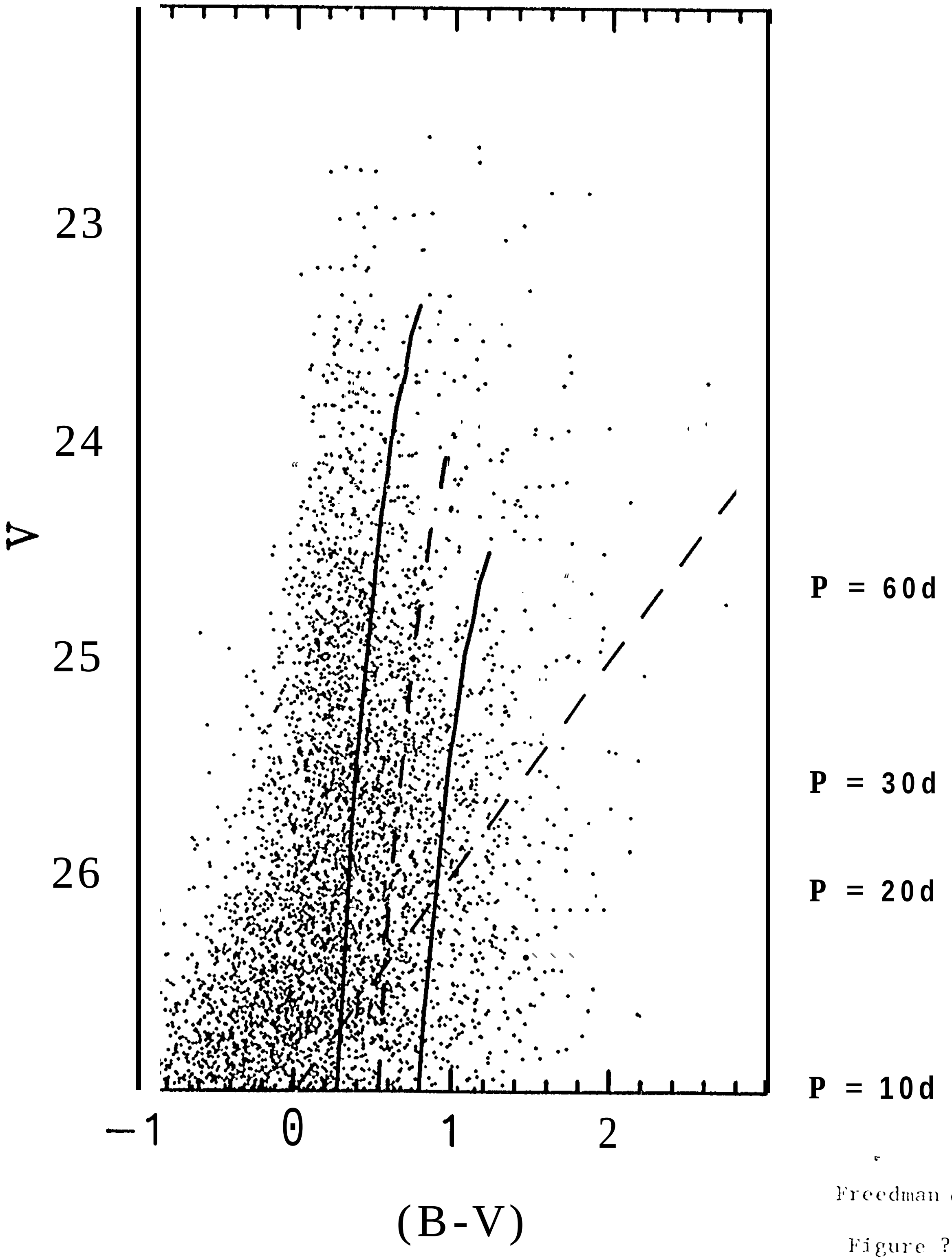
Tully, R. B. 1988, Nearby Galaxies Catalog, (Cambridge Univ. Press: Cambridge, England)



Freedman et al.

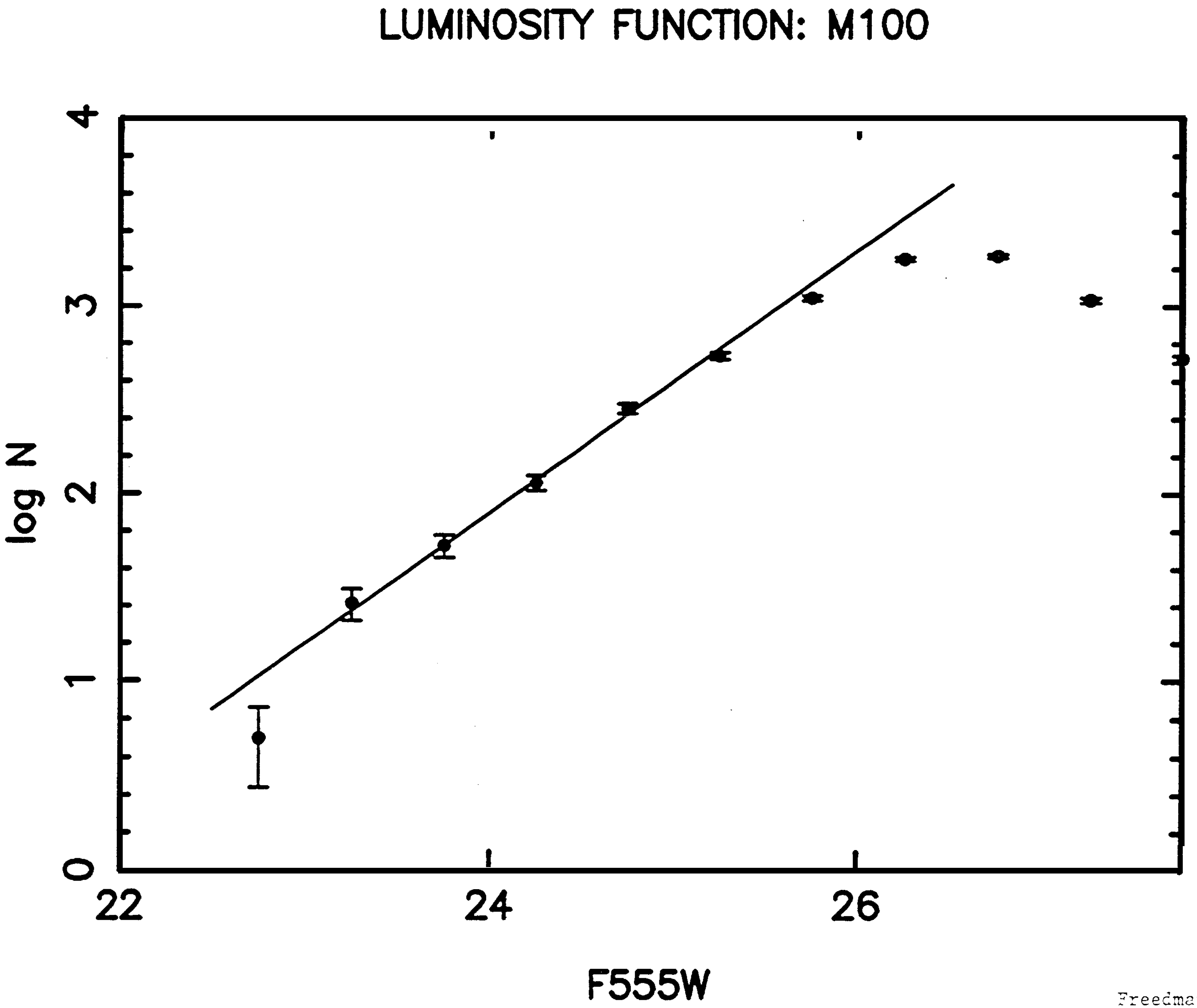
Figure 1

M1OO




Freedman et al .

Figure ?




Freedman et al

Figure 3